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PREFACE

A recent working paper by Pierre Crosson[1] provides an intellectual background for research being undertaken by FAP on "Limits and Consequences of Food Production Technologies". The primary focus of this research effort will be on developing a set of models that will increase understanding of the short and long-run impacts of policies on the resources-technology-environment (R-T-E) system in agricultural production.

This paper briefly sketches two model specifications that could be used to analyze the R-T-E issues discussed by Crosson. One model is specified to determine the "socially" optimal allocation of resources over time under R-T-E constraints, while the second model is specified to trace out the temporal R-T-E effects of agricultural producers' decisions under various R-T-E policies and assumptions. Both models are rather ambitious from a computational viewpoint and in terms of data requirements. It is suggested that initial modeling efforts focus on a few regions or watersheds, rather than countries. Then, as experience is gained with these small area models and information developed about the extremely complex R-T-E constraints, the modeling effort could be expanded to country models. Finally, country models could be linked to form a world R-T-E model.

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[1] Pierre Crosson, "Resources, Technology and Environment in Agricultural Development." WP-79-103, October 1979.

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Model specifications for analyzing the role and long-run impacts of resources, the environment, and technological change on the food production system.

C Robert Taylor

This paper briefly sketches two model specifications that could be used for analyzing the role and long-run impacts of resource availability, the environment, and technological change on the food production system of a country or, through linked models, on the world food economy. One model, which will be called the social decision model, could be used to determine the socially optimal allocation of resources over a long time horizon. This model is a dynamic optimization model that includes social welfare weights for current and future consumption, farm income, and the environmental costs of production. The objective function for this social model is specified for a developed market economy, but could be modified for other types of economies.

The second model, which will be called the producer model, is a recursive, static optimization model based on the relatively short-run decision horizon of farmers. The social model is normative, while the producer model is positive, predicated on the specified decision criterion of producers. A social model of this type is useful primarily in indicating the very best that society could do in terms of the spatial and temporal allocation of resources. Although the solution to the social model implies a set of taxes that could be imposed in a market economy to achieve the desired allocation of resources, the practical usefulness of this model may be quite limited. On the other hand, the producer model will predict the actual allocation of resources, technology and environmental quality under the assumption that producers make resource allocation decisions. As contrasted to the social model, the producer model can be used to evaluate the resource-technology-environmental-economic impacts of policies for which implementation is feasible. This model will predict short-run as well as long-run impacts of various policies.

Both models are specified under the following general premises.

1. That the models will emphasize resource-technology-environmental factors that may influence national or international production, and thus influence the price of agricultural commodities now or in the future. Consequently, price determination must be endogenous to the model; otherwise, economic implications will be erroneous.

   Factors that will not significantly influence national output can more appropriately be analyzed with small models. For example, policies to control nitrate pollution that occurs only in a small watershed can more effectively be analyzed with economic-physical models that deal only with that watershed and assume that any output changes will not influence price.

2. The problems that tend to be large enough to affect production and price, and thus the focus of this modeling effort, are: a) soil erosion (sheet, rill and wind) that reduces the future productivity of this resource; b) agricultural use of ground and surface water, with groundwater being an exhaustible resource; c) water quality, both from the viewpoint of environmental quality and irrigation water (e.g. salinity); d) exhaustible resource used by agriculture (aside from water and soil) or resources that at least have increasing extraction costs (e.g. phosphorus, potassium, energy); e) the development of pesticide resistance, especially for insect populations; and f) pesticide pollution.

   For generality, eutrophication and health hazard problems associated with plant nutrients are included in the models, but these problems do not appear to be widespread and thus could be more effectively addressed with problem specific models. But, these problem specific models should use prices, etc., from aggregative models of the type presented in this paper.

3. Piece-meal analysis of environmental-resource-

technology considerations will not give the true picture of problems and economic impacts of policies.

4. Induced technological change will occur over time. This change can be either environmentally improving, or environmentally damaging, depending on the forces inducing the change. Technological change is viewed as directly altering production costs and/or production coefficients and/or resource availability.
5. For hydrological reasons, watersheds are the appropriate unit of analysis. A country's land resources are viewed as being comprised of many small watersheds, linked by downstream movements of soil and pollutants, and also linked by economic interdependencies.
6. Because the models address (in part) long-run soil productivity and because crop comparative advantage differs by soil, it is imperative that the models account for different soil-type-slope-erosion capability classes in each watershed. The number of soil classes and watersheds to delineate for a study area will be determined by a) computational considerations; and b) desired accuracy of model results.
7. The models need to account for both energy demand and supply by agriculture. On the demand side, energy saving technology must be considered, while on the supply side the potential of producing methane from livestock wastes and producing ethanol from

grain and/or crop residues should be considered.

8. Due to the dynamics of the system, a long (perhaps infinite) time horizon should be used for the analysis.

THE SOCIAL MODEL

For the social model, it is assumed that consumers' plus producers' surplus less external costs associated with pollution is a reasonably valid measure of the net social benefits associated with the agricultural system. This social welfare function is valid only for a developed economy. For developing economies this function could be replaced by a function that used more appropriate welfare weights for nutrition, consumption, environmental quality, etc. Or, if appropriate, a goal-programming approach could be used.

The non-agricultural sector is ignored in the model outlined here, but could be included in an expanded model specification. To simplify notation, the interregional transportation of commodities is not included in the model specification. Livestock are also excluded from the specification to simplify notation.

Assuming that economic surplus less external costs is a valid measure of social welfare in a given time period, welfare over a long time horizon can be viewed as the present value of a stream of surpluses and external costs. Hence, a social objective function for the problem at hand can be specified as:

$$\max_{A,X} \; J = \sum_{t=1}^{N} \beta^{t} \underbrace{\left\{ \underbrace{\underbrace{\sum_{j} \int_{0}^{Q^{*}_{jt}} H_{jt}(Q_{jt})\, dg}_{\substack{\text{Area under demand}\\ \text{curves}}} - \underbrace{\sum_{j} \sum_{i} \sum_{l} \sum_{m} C_{tjilm} A_{tjilm}}_{\substack{\text{Variable production}\\ \text{cost}}}}_{\text{Consumers' plus producers' surplus}} - \underbrace{D_{t}(S_{t}, X_{tjilmk})}_{\substack{\text{External costs}\\ \text{associated with}\\ \text{sediment, irrigation}\\ \text{return flow and}\\ \text{fertilizer and}\\ \text{pesticide inputs to}\\ \text{agricultural production}}} \right\}}_{\text{Present value of net social benefit over an N period horizon}} . \tag{1}$$

where

β = social discount factor

t = time index

N = social planning horizon (may be infinite)

j = commodity index

H_{jt} = compensated demand curve for commodity j

Q^*_{tj} = market clearing quantity of commodity j in period t

i = watershed index

l = soil index

m = production process index (conservation practice, tillage system, irrigation method, etc.)

C_{tjilm} = variable production costs per planted acre

A_{tjilm} = planted acreage

D_t = external costs associated with agricultural pollution (pesticides, fertilizers, water quality, sediment, etc.)

S_t = sediment load

X_{tjilmk} = per acre rate for the $k^{\underline{th}}$ input (e.g. k = fertilizer, pesticides, irrigation water)

The socially optimal resource use policy for each period of the planning horizon can be found by maximizing equation (1) subject to a set of economic, resource, technological, and environmental constraints and relationships. Constraints and relationships include the following:

Demand-Supply Identity:

$$(2) \quad Q_{jt} = \sum_i \sum_l \sum_m Y_{tjilm} A_{tjilm}$$

where

Y_{tjilm} = yield per planted acre

Production functions:

(3) $Y_{tjilm} = f_1(X_{tjilmk}, T_{tjilr}, B_{tjilmr}, W_{ti}, E_{(t-1)jilm},$

$\ldots, E_{1jilm}, \tilde{Y}_{0jilm})$

where

E_{tjilm} = erosion rate

$\tilde{Y}_{ojilm}$ = measure of initial soil productivity

T_{tjilm} = technology variable

W_{ti} = weather index for watershed i

B_{tjilm} = measure of infestation, of pest r prior to control

Erosion relationship:

(4) $E_{tjilm} = f_2(A_{tjilm})$

Sediment load relationship:

(5) $S_t = f_3(E_{tjilm})$

Land constraint:

(6) $\sum_j \sum_m A_{tjilm} \leq L_{til} \qquad \forall\ i, t, l$

where

L_{til} = total available acreage of soil class l in watershed i in period t.

Annual irrigation water constraint (where appropriate)

(7) $\sum_j \sum_m \sum_i X_{tjilmk} \leq \tilde{W}_{tlk}$ $\forall$ t, l, k = water inputs

where

$\tilde{W}_{tlk}$ = maximum amount of irrigation water available in watershed l in period t

And for exhaustible water sources

(8) $\Sigma_t \tilde{W}_{tlk} \leq W^*_{lk}$

Other exhaustible inputs

(9) $\sum_t \sum_j \sum_i \sum_l \sum_m X_{tjilmk} \leq X^*_k$ for appropriate k

Pesticide resistance:

(10) $Z_{tr} = f_4 \; (Z_{(t-1)r}, X_{tjilmk})$ k = pesticides

where

Z_{tr} = resistance level for the 1th pest species in period t

Pest population dynamics:

(11) $B_{tjilmr} = f_5(B_{(t-1)jilm}, Z_{tk}, X_{(t-1)jilmk})$

Variable production cost relationship

(12) $C_{tjilm} = f_6(X_{jilmk}, T_{tjilm}, W_{tl}, R_{tk})$

where

R_{tk} = cost of the kth input

Input supply prices and/or extraction costs

(13) $R_{tk} = f_7(A_{tjilm} \; X_{tjilm}, \ldots, A_{0jilm} \; X_{ojilm})$

Induced technological change

(14) $T_{tjilm} = f_8\ (T_{0jilm}, \ldots, T_{(t-1)jilm}, R_{tk}, \ldots)$

FURTHER DISCUSSION OF THE SOCIAL MODEL

Control variables in this model specification are acreages, A_{tjilm}, and input rates, X_{tjilmk}. Optimal values for these variables imply market clearing prices, quantities, etc., and the time path of induced technological development.

Technological change depends to some extent on public R & D expenditures. If these expenditures can also be controlled, then they should also be considered variables in the model. And, in this case, the expenditures should be subtracted from the objective function (1) in order to account for all social benefits and costs.

The model solution will be especially sensitive to the social discount rate, β, and to projections of future demand, H_{tj}. Consequently, various scenarios for the discount rate and future demand will need to be considered in any applications of this type of model.

Costs associated with agriculturally related pollution are explicitly incorporated into the above model specification. Future social benefits associated with resource conservation are implicitly incorporated into the specification: Current levels of resource use (i.e. erosion, water use, other input use) affect the future productive potential of agriculture via equations (2) through (12) (not necessarily inclusive), which is reflected in the objective function for future periods. Thus, this dynamic optimization model will give the socially optimal allocation of resources over time, considering predicted induced technological change.

It is evident that many of the relationships in the model (e.g. (3), (5), (8), (10), (11), and (14)) cannot be accurately reflected in a few algebraic equations. Consequently, systems models of these relationships will have to be constructed. Then, a hierarchy of these models will have to be formed and called by a numerical optimization routine. Because of the large number of control variables for a realistic model and the complexity of relationships, numerical solution of such a model will be quite expensive.

Empirical application of the social model specified above would be a most ambitious undertaking; however, even more ambitious models can be specified. A less ambitious undertaking would be to develop a model only for a few representative watersheds or for problem watersheds. But to accurately measure economic factors, price determination should still be endogenous to the approach.

PRODUCER RESPONSE MODEL

The objective function for the producer model can be specified as follows

$$(15)\quad \max_{X,A} J_z = \sum_j \left[\sum_i \sum_l \sum_m (P^*_{tj} Y_{tjilm} - C_{tjilm} + K_{tjilm}) A_{tjilm}\right]$$

where

P^*_{tj} = expected price of commodity j

$$K_{tjilm} = \sum_{t=t+1}^{N_p} [P^*_{tj} Y_{tjilm} - C_{tjilm}] \beta_t$$

= incremental present value (from period t+1) return (or cost) to measure expected future on-farm consequences of current actions if producers have a multi-period planning horizon

with other variables as defined previously.

The term K_{tjilm} is included in the objective function to approximate a multi-period planning horizon with a static model. For example, soil conservation practices adopted now affect future yield levels. The coefficient K_{tjilm} should reflect the future value of this relative future yield increase. Although a multi-period optimization model would be more appropriate, this static specification is suggested to reduce computational cost. It is believed that the bias introduced by this specification will be reasonably small for most problems.

Equation (15) is maximized subject to:-

Land constraint:

(16) $\sum_j \sum_m A_{tjilm} \leq L_{til} \qquad \forall\ i,\ l$

Annual water constraint (where appropriate):

(17) $\sum_j \sum_m \sum_i X_{tjilmh} \leq \tilde{W}_{tlk} \quad \forall\ l,\ k$ = water inputs

Production function:

(18) $Y_{tjilm} = f_1(X_{tjilmk}, T_{tjilm}, B_{tjilmr}, W_{ti},$

$E_{(t-1)jilm}, \ldots, E_{1jilm}, \tilde{Y}_{0jilm}, V_{tjilm})$

where

V_{tjilm} = an index of the adoption rate for available technology, T_{jilm}

with

(19) $V_{tjilm} = f(t, T_{tjilm})$

Variable production cost

(20) $C_{tjilm} = f_6(X_{tjilmk}, T_{tjilm}, V_{tjilm}, W_{tl}, R_{tk})$

The production function (18) and cost function (20) are the same as the respective functions in the social model, except that adoption of profitable new technologies is no longer assumed to be instantaneous. A variable V_{tjilm} is introduced to account for the effect of non-instantaneous adoption on cost and yield. This specification introduces adoption by averaging yield and costs over the technologies used in period t. Although this averaging introduces a bias in the model specification, it is necessary to avoid an expanding grid for the static optimization model.

Additional constraints can be introduced into the above optimization model to reflect environmental quality and/or resource policy constraints. Moreover, the objective function can be modified to reflect policies which are intended to internalize externalities associated with agricultural production.

RECURSIVE LINKAGES FOR THE PRODUCER MODEL

Once a solution to the above model for resource allocation in period t is obtained, market clearing prices can be obtained by simultaneous solution of

(21) $Q^*_{jt} = H^{-1}_{jt}\ (P_{jt}) \qquad \forall\ j$

where

Q^*_{jt} = production in period t given by the optimization model

$H^{-1}_{jt}\ (P_{jt})$ = demand function

Then expected prices for the next period can be obtained from an empirical price expectation model

$$(22)\quad P^*_{j(t+1)} = f(P_{jt}, \ldots, P_{j0}) \qquad \forall\ j$$

Environmental effects associated with the model solution can be computed from

$$(23)\quad E_{tjilm} = f(A^*_{tjilm}) \qquad \text{erosion}$$

$$(24)\quad S_t = f(E^*_{tjilm}) \qquad \text{sediment}$$

$$(25)\quad \text{Ƶ}_{tr} = f(\text{Ƶ}_{(t-1)r}, X^*_{tjilmk}) \qquad \text{pesticide resistance}$$

and external costs can be computed from

$$(26)\quad D_t = f(S^*_t, X^*_{tjilmk})$$

Consumers' surplus can be computed from the demand curves, H_{tj}, given the market clearing price P_{tj}. Actual producers' income can be computed from P_{tj}, A^*_{tjilm} and X^*_{tjilm}. Thus, the social welfare impacts of producers' decisions (either constrained or unconstrained by resource-environmental policies) can be obtained as consumers' surplus plus farm income, less external costs (26). Welfare measured by this model could be compared to welfare obtained from solution of the social model, to judge how near policies would come to achieving the socially optimal allocation of resources.

Resource-environmental-technological factors constraining producers' decisions in the next year can be based on

(27) $Z_{tr} = f(Z_{(t-1)r}, X^*_{tjilmk})$

(28) $B_{(t+1)jilmr} = f(B_{tjilmr}, Z_{tr}, X^*_{tjilmk})$

Actual input prices in period t can be determined from a function similar to equation (13) in the social model

(29) $R_{tk} = f(A^*_{tjilm}, X^*_{tjilmk}, \ldots)$

and induced technological change for the next period is given by

(30) $T_{(t+1)jilm} = f(T_{tjilm}, \ldots, T_{0jilm}, R_{tk})$

DISCUSSION OF THE TWO MODELS

From a computational viewpoint, the social model is by far the most ambitious, as the model requires a hierarchy of physical and biological systems models which must be repeatedly called in a numerical optimization routine. The producer model is less ambitious from a computational viewpoint because it is much less costly to repeatedly solve a static model than to solve the dynamic optimization model. Also, the physical and biological systems models would have to be used only once in each period.

In terms of data requirements, the models are equally ambitious, although the producer model could be implemented without knowledge of the external costs of pollution (equation (26)).

The producer model is likely to be much more useful in a practical sense because it could be used to evaluate policies for which implementation is feasible, while the social model only identifies the "best" allocation of resources. In all likelihood, the allocation of resources obtained from the social model could not be implemented and second best resource allocations would have to be found.

Theoretically, even more elaborate and ambitious models could be specified. However, the two specifications outlined here are regarded as the limit of what would be empirically operational and computationally feasible at the present time.